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PERFORMANCE REPORT

Neural Networks for Real-Time Sensory Data Processing and Sensorimotor Control

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Randall D. Beer
Principal Investigator
Department of Computer Engineering and Science
Department of Biology
Case Western Reserve University
Telephone: (216) 368-2816

Over the past six months, we have begun to lay the groundwork for the work described in our new ONR grant entitled "A Biologically-Inspired Autonomous Robot". We have been meeting every other week since the beginning of September to formulate detailed plans for the initial phase of this research. In addition, preliminary work on a number of initial milestones of this research has begun. Our accomplishments to date and some immediate future plans are summarized below.

Our experimental work has focused upon a precise description of the wind fields for individual type A thoracic interneurons (TI_As) and beginning to describe the leg movements associated with individual leg motor neurons. In the first set of experiments, Songhai Chai (a graduate student supported on the ONR grant) has moved from his studies on paired GI responses to the wind responses of the thoracic interneurons that receive inputs from the GIs. Although the basic wind field properties for the entire population were described earlier (Westin et al, 1988), we do not have the precise wind fields for individual interneurons. This information is necessary for further development of the escape model and for future experiments that will utilize the computer model to determine the extent to which wind field properties are due to convergence of vGI inputs.

Songhai Chai has now made considerable progress on these experiments. We are confident of the fields of at least two TI_As (301 and 701), and these properties are consistent with our information on pattern of vGI connections with these interneurons. Preliminary results on several other interneurons are also encouraging. If the experiments continue as well as they have in recent months, we anticipate having much of the information needed by the end of next year. We can then continue with questions of how much other wind receptive inputs, such as information descending from the head, influence these fields. Ultimately, these studies will have important implications on how turning movements are controlled by a population of interneurons. As such, the results will be meaningful both for the escape system and for design of turning control circuits in the robot that is being designed in the renewal period for the project.

The studies on control of leg movements will have direct bearing on the robot project. Ultimately, we would like to be able to model the total neural control of leg movements during walking. As a first step, we have begun to model the control of a single metathoracic leg. For our part, we intend to map the neural inputs to the majority of muscles, document the movements that each neuron evokes and the transfer function to muscle activity. In conjunction with Dr. Robert Full, who is making force measurements and has developed a three dimensional reconstruction of the leg and Dr. Sasha Zill who is investigating the sensory structures of the leg, this work will provide a remarkably detailed description of the control of movement in this leg. We have been in close contact with both of these investigators. Dr. Full visited our lab in November, we plan to visit Dr. Zill's lab early in January

To accomplish our end of this project, Dr. James Watson (a postdoctoral researcher who will be funded on the renewal of the grant) has developed a preparation whereby he can impale a single neuron, stimulate it intracellularly and monitor the resulting leg movement with video motion analysis. Resulting muscle activity is monitored with EMG electrodes and movement of the leg is recorded with our high speed video system. Using the wave inserter option on the video system we can superimpose the EMG record from the muscle in the video record. In this way, we will acquire precise data on timing and extent of motion at each joint for each individual motor neuron and for local interneurons that drive coordinated groups of motor neurons. Although these experiments have just begun, Dr. Watson has already described one motor neuron that controls flexion of distal tarsal segments and one interneuron that appears to able to drive patterned activity similar to that responsible for walking.

Parallel development of computer models of both the insect and the robot are a key component of our research. We spent one entire meeting discussing in great detail the features of the simulation environment that will be required to support both the physiological modeling of the insect and the development of the robot and its neural controllers. These discussions have precipitated a number of revisions in the structure of the software which have recently been undertaken.

William Marx, an AASERT student in Biomedical Engineering that is attached to this grant, began working with us this summer. In addition to course work, he has been participating in our group discussions since the beginning. He has begun the implementation of a biomechanical model of a single leg which will be integrated into the simulation environment when it is completed. This model will capture the essential degrees of freedom observed during walking and will include muscle data derived from Bob Full's current work. When completed, the model will allow us to synthesize results from the recently started motor neuron mapping experiments described above. With this model, we can begin to explore how patterns of motor neuron activation generate observed leg movements. Eventually, a full dynamic model of the complete insect will be constructed.

We have built a prototype robot leg with three degrees of freedom. The construction is predominantly balsa, aircraft plywood, and aluminum. The tube-like leg segments are coated with a mylar covering which increases surface toughness and rigidity. The tarsus is made of aluminum and contains two semiconductor strain gages to measure the foot load. Each joint contains ball-bearings for durability and smoothness of operation. Due to our belief that mechanical energy storage plays a major role in enhancing the performance of insects, we have experimented with the concept of mechanically storing energy on the robot, specifically through the use of flexible components in the leg segments.

Two prototype joint position controllers have been constructed. One makes use of analog hardware and uses proportional feedback control, with a provision for adding derivative control. The other controller uses digital circuitry and pulse-width modulation to vary the output to the motor. A microprocessor, which recently became commercially available, capable of controlling 12 motors is being used for this digital implementation. We plan to test this microprocessor on the prototype leg, controlling its three motors, before deciding which technology to use.

We have also constructed an experimental neural network controller which generates a basic stepping cycle for the new kinematics of the prototype leg. In addition, this controller implements some of the reflexes found in insect legs. For example, when the leg is in the swing phase and an obstacle is encountered, the leg backs off slightly and attempts to lift and swing forward again in hopes of avoiding the obstacle.

We have been conducting a review of the literature regarding insect leg reflexes and their neural basis. In particular, we have been forming a foundation of neurobiological concepts upon which to base our next robot controller. We have been focusing on two main topics: First, we have been compiling a list of the desired reflexes required for basic locomotion and rough terrain negotiation. These may be classified into two categories: postural reflexes and walking reflexes. Postural reflexes include reflexes the insect uses in the basic task of maintaining posture. For example, if the body is perturbed slightly, the muscles act in such a way that the generated forces counteract the imposed motion of the body. Our investigation of postural reflexes has concentrated primarily on the work of Sasha Zill. We are categorizing the walking reflexes into six categories: stance initiation, maintenance, and termination; and swing initiation, maintenance, and termination. So far we have investigated Pearson and Franklin's description of some of the reflexes which occur during insect walking across a variety of terrain. Our second point of focus is to develop a foundation for the basic architecture of the neural controller. By studying the types of neurons in the insect nervous system, how they are interconnected, and the functions that each type performs, we can form an analogous architecture for our controller. In this effort, we have focused mainly on the work of Malcolm Burrows.

Publications

Gallagher, J.G. and Beer, R.D. (in press). A qualitative dynamical analysis of evolved locomotion controllers. To appear in the Proceedings of the Second International Conference on Simulation of Adaptive Behavior.

Chiel, H.J. and Beer, R.D. (in press). Neural and peripheral dynamics as determinants of patterned motor behavior. To appear in D. Gardner (Ed.), *The Neurobiology of Neural Networks*. MIT Press.

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Beer, R.D., Ritzmann, R.E. and McKenna, T., Eds. (1992). *Biological Neural Networks in Invertebrate Neuroethology and Robotics*. Academic Press.

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Submitted

Beer, R.D. A dynamical systems perspective on autonomous agents. Submitted to *Artificial Intelligence*.

Espenschied, K.S., Quinn, R.D., Chiel, H.J. and Beer, R.D. Leg coordination mechanisms in stick insect applied to hexapod robot locomotion. Submitted to *Adaptive Behavior.*

Quinn, R.D., Beer, R.D, Chiel, H.J., Espenschied, K and Larsson, P. Biologically-inspired neural control of a mechanical hexapod. Submitted to *ASME J. of Dynamic Systems, Measurement and Control.*